

THE OPTICAL GRAVITATIONAL LENSING EXPERIMENT.
THE EARLY WARNING SYSTEM.

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The discoveries of 17 microlensing event candidates have been reported over the last year by three teams conducting unprecedented mass photometric searches in the direction of the Galactic bulge and the Magellanic Clouds. These include 10 events found by the OGLE collaboration^{1,2,3,4}, 5 by the MACHO team^{5,6} and 2 by the EROS team⁷. All searches have the main goal to detect dark matter in our Galaxy. The detection of 17 event candidates proves that the microlensing is a powerful tool in the search for dark matter^{8,9}, and it may be used for reliable mass determination when the geometry of the event is known. Here we present the first microlensing event, OGLE #11, discovered in real time, using the newly implemented "Early Warning System". We describe our system which makes it possible to monitor and study in great details any very rare phenomena, not only lensing events, with a broad array of instruments almost immediately after they have changed their brightness.

The probability of occurrence of gravitational microlensing is very small even in the dense stellar fields of LMC or the Galactic bulge. The first estimate of the optical depth to gravitational microlensing towards the Galactic bulge is $\sim (3.3 \pm 1.2) \times 10^{-6}$ ³. Thus observations of millions stars conducted over a period of years are necessary to collect a significant sample of events. The OGLE project has conducted its search in the direction of

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the Galactic bulge since 1992 using the Swope 1-m telescope at Las Campanas Observatory, Chile, which is operated by Carnegie Institution of Washington. A 2048×2048 Loral CCD chip is used as the detector. Currently, about 6 millions photometric measurements of 4 millions bulge objects are collected during each clear night.

The characteristic feature of such a massive survey is the tremendous data rate, and the greatest difficulty is the need to process the data quickly. Typically, the reductions are usually significantly delayed. Up to now, all microlensing events were announced well after the events had occurred, with delays ranging from 3 months (OGLE #1) to almost 3 years (EROS #2). All the lensed stars were back at their normal brightness when the actual discovery (as opposed to the observations) was made. This delay also introduces an important practical problem: the light curves of most previous microlensing events have non-uniform or sparse temporal coverage. This is partly due to uncontrollable factors such as poor weather or telescope scheduling (the latter is a particularly major limitation for OGLE which does not have a dedicated telescope). However, in many cases better data could have been obtained if the observers had known that some particular fields contained promising candidate events. Thus it became evident that we have to develop a system which would allow the detection of a microlensing event soon after it starts. Such an event could then be widely observed in all possible wavelength ranges photometrically as well as spectroscopically from many observatories around the world. Crucial parts of the light curve near maximum light could be covered with a very good time resolution. These parts of the microlensing light curve provide potential information about binarity of lensing star or even about possible planets around it¹⁰. Also, good coverage of the caustic crossings in double microlens events may provide important data about the structure of the lensed objects, and the determination of parameters of the binary lensing system⁴.

Beginning with the 1994 observing season (March-September) the OGLE project has implemented an "Early Warning System" (EWS) developed at Warsaw University Observatory¹¹. This software system is designed to detect on-going microlensing events and it opens a new era in massive photometric surveys by allowing early detection of microlensing phenomena and follow-up observations from other observatories. The sys-

tem was designed to detect any kind of transient and smooth stellar variability, not just microlensing.

The microlensing detection technique used by OGLE was described in details in a series of papers^{1,2,3}. To summarize, a database of about 2 million non-variable stars in 1992-93 seasons was constructed from the original database of all measured objects. All photometry was performed using a modified version of the DoPhot photometry program¹². On average, about 30 CCD frames of the Galactic bulge are collected during a night. The computer system consisting of multiprocessor Sparc 10 workstation is capable of reducing the data from a typical night within 24 hours. The new measurements of each object from the non-variable stars database is compared with its database mean magnitude. If the brightness differs more than a certain threshold appropriate to the mean magnitude of the star, the star is flagged by the EWS as suspected. Next, the EWS checks whether the brightness change is continuous. If the number of consecutive measurements giving the brightness above the threshold exceeds some fixed number then an alarm is issued. The threshold is set at three times the maximum allowed sigma of brightness for a non-variable star of given magnitude, and the number of consecutive observations above the threshold is set to five – a compromise between number of false alarms and detection delay. Both parameters can be tuned as needed depending on the type of variables one is searching for. Alarms are limited to objects which increase their brightness (like microlenses) but can easily be extended to include the objects whose magnitude steadily drops.

The light curves of the objects signalled by the EWS, are automatically e-mailed to the OGLE headquarter at the Warsaw University Observatory. Objects are further analyzed there to exclude obvious false alarms due to bad photometry, CCD detector blemishes etc. A variety of filters which reject random variability can be applied at that stage. For example, the errors of observation which are sensitive indicators of the quality of photometry, are analyzed. If the suspected object passes this step then visual inspection of the CCD frame is performed to check whether the photometry is not affected by CCD defects. Next, the light curve is analyzed for the microlensing type of light variability. If all tests are positively passed and brightening of the object is confirmed by two additional

observations, the suspected object is named a "prime microlens candidate" and a world-wide alarm is distributed to the astronomical community.

The EWS system had been intensively tested on real data from the previous seasons prior to its implementation. All earlier OGLE microlensing events were detected at the early stages of their development with no false alarms. The EWS system has been routinely used in the 1994 season. Soon after its implementation, a new microlensing candidate has been discovered. The object: BW6 Baade's Window field star¹³ I 167045, was detected by the EWS in July 1994. The star passed all additional criteria and a world wide alert was issued. The J2000.0 coordinates of the star are $\alpha_{2000} = 18^h 03^m 45^s.1$, $\delta_{2000} = -30^\circ 18' 16''.4$ and $66'' \times 66''$ region of the CCD frame around OGLE #11 is shown in Fig. 1.

As further data were obtained, we confirmed that the star is indeed a good microlensing candidate. Its light curve (complete through date) and the best fit to the theoretical microlensing curve is shown in Fig. 2. The solid horizontal line shows the mean 1992-93 magnitude, and the dashed line shows the threshold level. The vertical arrow points to the time of discovery. The event has been designated as OGLE #11. This event, OGLE #11, is the first microlensing event detected while it was still unfolding.

At the moment of discovery it was not clear whether the event is still on its rising part of the light curve. It turned out, however, that OGLE #11 is a low amplitude event and it reached the EWS threshold, and was discovered near the maximum brightness. Nevertheless the event could be followed during the descending branch of the light curve. The best-fit parameters of the OGLE #11 light curve are: time of maximum brightness, $T_{max}(\text{JD hel.}) = 2449537.3 \pm 0.7$; time scale (the Einstein radius / transverse velocity), $t_0 = 12.6 \pm 1.3$ days; magnification, $A = 1.32 \pm 0.02$; normal I magnitude, $I_0 = 18.22 \pm 0.01$; $\chi^2 (\text{dof}) = 0.72$.

The normal colors of OGLE #11 are $V = 19.7$, $V - I = 1.6$ indicating a normal Galactic bulge turn-off point main sequence star. OGLE #11 is one of the smallest amplitude events ever detected; its discovery dramatically proves the efficiency of the EWS system.

The EWS system is not only suited for classic microlensing. It detects any object

which increases its brightness in a continuous way. This way every strange object which changes its brightness after a long period of non-variability may be easily noticed. For example, the possible double microlens, OGLE#7⁴, which exhibited a very strange light variations, would have been detected during the event had the EWS been implemented in the 1993 season. It should be stressed here that any object changing its brightness after a long period (years) of remaining at constant level is potentially interesting and worth observing.

Up to now, only bright and obvious objects like novae or supernovae were detectable in real time, and still during the event. With systems like the EWS it is possible to register any on-going event which is characterized by a temporary change of its brightness. As mentioned above, the EWS can easily be tuned for objects which fade (eg. R Coronae Borealis stars). We also plan to extend the EWS to make it possible to detect in real time the objects which brighten but which are normally below the detection limit of the OGLE photometry.

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Figure Captions

Fig. 1. $66'' \times 66''$ fragment of *I*-band CCD frame around OGLE #11. Arrows point to the lensed star.

Fig. 2. The light curve of OGLE #11 in 1992 – 1994 observing seasons. Error bars correspond to estimated $1\text{-}\sigma$ errors. Thick solid line shows the constant light level from 1992-93 seasons, and dashed line – the EWS threshold. Vertical arrow points to the time of discovery. Thin solid line shows the best fit of the theoretical microlensing light curve.

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